

Study of Scaling in Hadronic Production of Dimuons

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We present proton-nucleus dimuon-production cross sections for masses between 4 and 15 GeV, center-of-mass rapidities between -0.23 and 0.6 and incident energies of 200, 300, and 400 GeV. The data confirm scaling to the 20% level. The dependence of continuum $\langle p_T \rangle$ on beam energy is also presented.

We have extended our study of muon-pair production by 400-GeV protons¹ to incident proton energies of 200 and 300 GeV. We find that a dimensionless form of the cross section can be well described at all three beam energies by a single function that depends only on dimensionless variables. Scaling of the cross sections in this manner implies the absence of any mass parameters with values similar to the relevant variables in the process, in this case the mass of the muon pair ($4 \leq m \leq 15$ GeV) and the total c.m. energy \sqrt{s} . An extensive literature² has appeared in which issues of scale breaking, asymptotic freedom, and QCD (quantum chromodynamics) act to modify the qualitatively successful par-

ton-annihilation model. It is these issues that we hope will be illuminated by the data presented here.

Figure 1 shows our mass spectra evaluated for the mean c.m. rapidity y of each data sample. We

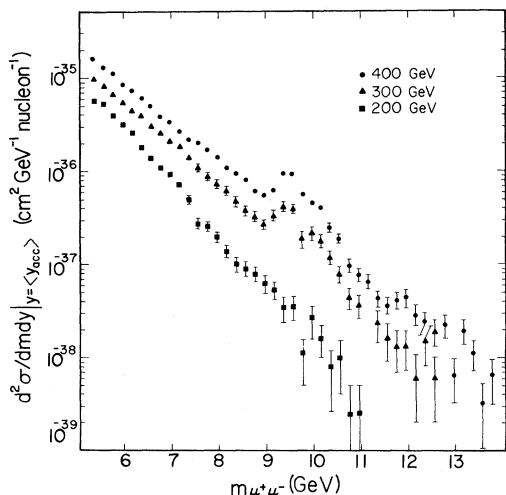


FIG. 1. $d^2\sigma/dm dy|_{y=y_{acc}}$ vs m for three beam energies.

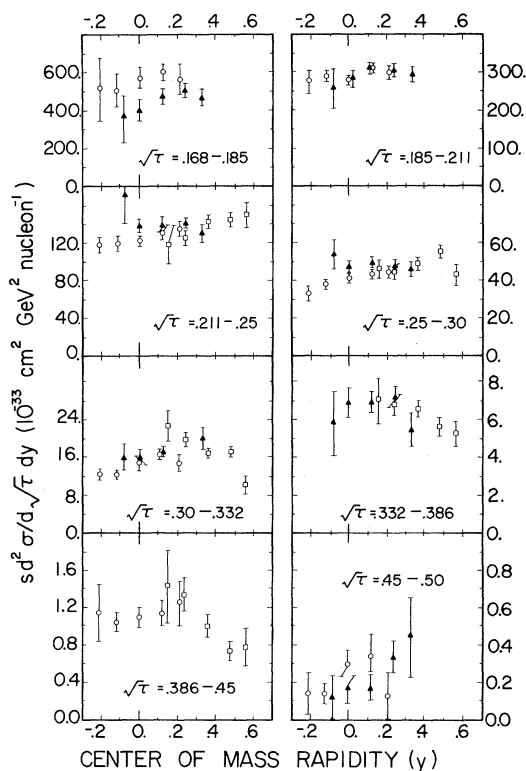


FIG. 2. $s d^2\sigma/d\sqrt{\tau} dy$ vs y for several $\sqrt{\tau}$ bins. Circles are $P_{beam}=400$ GeV, triangles are 300 GeV, and squares are 200 GeV.

TABLE I. Mass fit parameters. Continuum form, $d\sigma/dm dy = A e^{-bm}$. Cross sections are evaluated at $y = \langle y \rangle_{\text{acc}}$. (See Refs. 3 and 5.) An isotropic decay angle distribution is assumed for Υ production. For the continuum $1 + \cos^2\theta$ in the Gottfried-Jackson frame is assumed. These cross sections supersede those given in Ref. 1.

P _{beam} GeV	200	300	400
$\langle y \rangle_{\text{acceptance}}$	0.40	0.21	0.03
A nb/GeV	$10.4 \pm 1.1 \pm 2.2$	$2.47 \pm 0.03 \pm 0.5$	$2.70 \pm 0.02 \pm 0.5$
b GeV ⁻¹	$1.39 \pm 0.02 \pm 0.02$	$1.04 \pm 0.01 \pm 0.02$	$0.97 \pm 0.01 \pm 0.02$
χ^2/DF	42/34	35/54	78/74
m(T) GeV	9.46 (fixed)	$9.45 \pm 0.02 \pm 0.10$	$9.46 \pm 0.012 \pm 0.10$
B d σ /dy pb	0.002 ± 0.002	0.094 ± 0.012	0.29 ± 0.012
m(T'-T) GeV	0.6 (fixed)	$0.69 \pm 0.05 \pm 0.05$	$0.60 \pm 0.03 \pm 0.05$
B d σ /dy T'/T	0.67 ± 0.94	$0.46 \pm 0.09 \pm 0.10$	$0.38 \pm 0.04 \pm 0.10$
m(T''-T)	1.0 (fixed)	1.0 (fixed)	0.97 ± 0.10
B d σ /dy T''/T	0.10 ± 0.6	0.00 ± 0.08	$0.08 \pm 0.04 \pm 0.04$
χ^2/DF	12.6/19	12.1/16	14.7/16
T/cont. GeV	0.1 ± 1	0.67 ± 0.10	0.97 ± 0.05
T'/cont. GeV	-	0.58 ± 0.14	0.66 ± 0.08
T''/cont. GeV	-	0.00 ± 0.13	0.19 ± 0.12

have fitted these data excluding the 8.8–11-GeV (Υ) region with linear exponential curves, subtracted the fit from the data, and tested the remainder for enhancements in the excluded region. We list the results of the continuum and the Υ fits³ in Table I. We note that the acceptance in y is roughly Gaussian with a full width at half-maximum of 0.4 units. Since the laboratory angle of the spectrometer is fixed, the center of this acceptance shifts with incident beam energy as indicated in Table I.

In Fig. 2 we present a dimensionless form of the cross section, $s d^2\sigma/d\sqrt{\tau} dy$, in bins of $\sqrt{\tau} = M/\sqrt{s}$ as a function of y . We assume a dimuon decay distribution $1 + \cos^2\theta$ in the Gottfried-Jackson

frame and integrate over dimuon transverse momentum p_T ; data in the Υ region have been excluded. The major systematic uncertainty is the relative normalization between data taken at different beam energies. We estimate $\pm 5\%$ between 200 and 300 GeV and $\pm 10\%$ between 200 or 300 GeV and 400 GeV. We note that the acceptance in y is far from ideal for purposes of extracting y behavior. This results in an extra systematic uncertainty of $\pm 10\%$ at the acceptance edges. If scaling is assumed, the data in Fig. 2 represent measurements of the y dependence for $-0.23 < y < 0.6$.

In Fig. 3(a), we present the cross sections at $y = 0.2$ (where all three energies overlap) versus $\sqrt{\tau}$. We find the results consistent with a global fit^{4,5}:

$$s d^2\sigma/d\sqrt{\tau} dy|_{y=0.2} = (44 \pm 0.7 \pm 12.0) \exp[-(25.3 \pm 0.2 \pm 0.6)\sqrt{\tau}] \mu\text{b GeV}^2, \quad (1)$$

with a χ^2 per degree of freedom of 173/145 (confidence level=10%). Figure 3(b) displays the ratio of the cross section of Fig. 3(a) and this global fit. The contrast between Figs. 1 and 3 illustrates the significance of the scaling test. We note that scale breaking at the level observed in deep inelastic

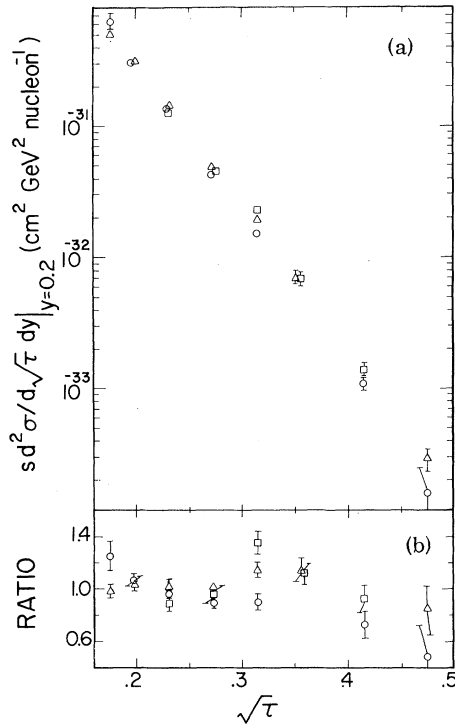


FIG. 3. (a) $s d^2 \sigma / d\sqrt{\tau} dy|_{y=0.2}$ vs $\sqrt{\tau}$. Circles, triangles, and squares correspond to 400-, 300-, and 200-GeV beam energy, respectively. (b) Above data divided by the overall fit $A e^{-b\sqrt{\tau}}$.

scattering would have no effect at $\sqrt{\tau}=0.2$ and would cause the 200-GeV data points to be on the order of $\sim 20\%$ above the 400-GeV data at $\sqrt{\tau}=0.5$.²

Figure 4 graphs the relative y slope of $s d^2 \sigma / d\sqrt{\tau} dy$ at $y=0$ versus $\sqrt{\tau}$ for the 400-GeV data. Positive slopes indicate a strong forward-backward asymmetry. One expects asymmetry since our target nucleon is on average 40% proton and

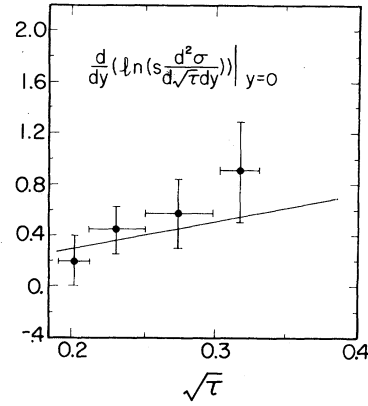


FIG. 4. The relative slope of the y distribution at $y=0$ vs $\sqrt{\tau}$ for the 400-GeV data. The curve is a result from a parton-annihilation-model calculation.

60% neutron. Figure 4 also indicates that the observed y behavior is consistent with that expected from the parton-annihilation model fitted to our 400-GeV data¹ with an SU(3)-symmetric sea.

The naive parton-annihilation model predicts that the p_T dependence of the invariant cross section should vary only with $\sqrt{\tau}$ and y . We find the p_T dependence well represented by the form

$$E d^3 \sigma / dp^3 = C [1 + (p_T/P_0)^2]^{-6}, \quad (2)$$

with parameters P_0 and C given in Table II. Our results for $\langle p_T \rangle$ (calculated from the data) are shown in Fig. 5 along with data at lower masses.⁶ We have ascertained that $\langle p_T \rangle$ does not vary significantly over our y range.⁷ For $m > 5$ GeV, and excluding the Υ region, $\langle p_T \rangle$ is independent of mass but rises with beam energy. This may

TABLE II. p_T fit parameters. $E d^3 \sigma / dp^3 = C [1 + (p_T/p_0)^2]^{-6}$. Significant data extend to about 3 GeV/c in p_T (see Kaplan *et al.*, Ref. 1). Errors in this table are statistical only.

M	$\sqrt{s}=19.4$ GeV		$\sqrt{s}=23.7$ GeV		$\sqrt{s}=27.3$ GeV	
	C (fb GeV ⁻²)	P_0 (GeV)	C (fb GeV ⁻²)	P_0 (GeV)	C (fb GeV ⁻²)	P_0 (GeV)
4.5	7169 ± 208	2.07 ± 0.049	9006 ± 250	2.25 ± 0.055	10310 ± 419	2.62 ± 0.095
5.5	1592 ± 59	2.34 ± 0.055	2648 ± 79	2.41 ± 0.044	2887 ± 55	2.70 ± 0.035
6.5	470 ± 21	2.34 ± 0.061	842 ± 30	2.60 ± 0.055	1058 ± 25	2.74 ± 0.036
7.5	121 ± 9.9	2.19 ± 0.099	326 ± 16	2.59 ± 0.068	386 ± 13	2.86 ± 0.050
8.5	26.3 ± 4.4	2.01 ± 0.186	104 ± 8.0	2.53 ± 0.097	163 ± 6.4	2.78 ± 0.050
9.5	7.22 ± 2.07	2.29 ± 0.393	70.5 ± 5.5	2.65 ± 0.111	130 ± 5.6	3.10 ± 0.075
10.5			19.3 ± 3.0	2.65 ± 0.247	41.8 ± 3.1	2.83 ± 0.112
11.5					10.2 ± 1.9	2.21 ± 0.202

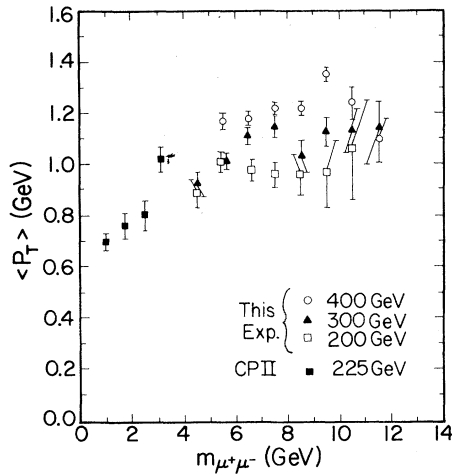


FIG. 5. $\langle p_T \rangle$ vs m for three beam energies. The data below $m_{\mu^+\mu^-} = 4$ GeV are from Ref. 6 (CPII).

be described by

$$\langle p_T^2 \rangle = \alpha + \beta s, \quad m > 5 \text{ GeV}, \quad (3)$$

where $\alpha = 0.70 \text{ GeV}^2$ and $\beta = 0.0018$. Although the disagreement with the naive parton-annihilation model is clear, this result is not in contradiction with QCD calculations.² The parameter α presumably represents the "intrinsic" quark transverse momenta.

In conclusion, we have presented excitation data for Υ , Υ' , and Υ'' production. The dimuon continuum cross sections scale over the energy and mass range studied. The y distributions exhibit a forward peaking consistent with parton-annihilation models. The p_T distributions imply that $\langle p_T \rangle$ increases with energy at fixed m/\sqrt{s} .

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¹S. W. Herb *et al.*, Phys. Rev. Lett. **39**, 252 (1977); W. R. Innes *et al.*, Phys. Rev. Lett. **39**, 1240, 1640(E) (1977); D. M. Kaplan *et al.*, Phys. Rev. Lett. **40**, 435 (1978).

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³The cross sections in Table I have been corrected for Fermi motion in the nuclear targets to yield the cross section at the \sqrt{s} for a proton-nucleon collision. This correction is approximately given by

$$\begin{aligned} d^2\sigma/dm dy|_{\sqrt{s} \text{ proton-nucleon collision}} \\ = e^{-0.82(\sqrt{\tau}-0.2)} d^2\sigma/dm dy|_{\sqrt{s} \text{ observed}} \end{aligned}$$

for $0.2 \leq \sqrt{\tau} \leq 0.5$. All other data reported have been corrected for Fermi motion.

⁴The relative normalizations between cross sections measured at different energies were treated as data with errors equal to their systematic uncertainties. The fit was as follows:

	Input	Fit
(400 GeV)/(300 GeV)	1.0 ± 0.10	1.01 ± 0.01
(200 GeV)/(300 GeV)	1.0 ± 0.05	1.01 ± 0.03

⁵Except where noted, when two errors are given the first is statistical and the second systematic. When one error is given it is the combined error.

⁶J. G. Branson *et al.*, Phys. Rev. Lett. **38**, 1334 (1977).

⁷We have examined separately the data with $p_T > 1 \text{ GeV}/c$ and observe no qualitative differences in the s or y behavior of this subset. The p_T dependence of dilepton production poses a serious challenge to perturbative QCD calculations. See Ref. 2.